INSTITUT d'OPTIQUE GRADUATE SCHOOL ParisTech | LEnsE Laboratoire d'Enseignement Expérimental

Lab work in photonics.

Photometry and sources.

Rooms	**Ph1**	**Ph2**	**Ph3**	**Ph4**
	S1.27	S1.11	S1.31	S1.23

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Engineer - 2nd year - S7 -Palaiseau
Version : August 31, 2021
Year 2021-2022

Lab work 1

Measuring luminance

Version: August 31, 2021

Questions P1 to P4 must be prepared in advance

The report must be sent within one week. Its length must be 8 pages maximum.

Contents

The goal of this lab session is to learn some commonly used radiometric measurement techniques. They are based on simple principles but must be conducted with care. In photometry, measurements rarely have an accuracy better than 5 to 10 %. Care should be taken during the entire course of the lab, analyzing as well as possible the sources of uncertainty and their influence on the measurements.

1 Calibration of a visible photodiode

The `UDT PIN 10AP` photodiode is equipped with a green optical filter in order to reproduce the spectral response of the human eye (see Figure 1.1). Visual quantities can therefore be directly measured with this kind of photodiode. The area of the detector is $S = 1.000\,\text{cm}^2$.

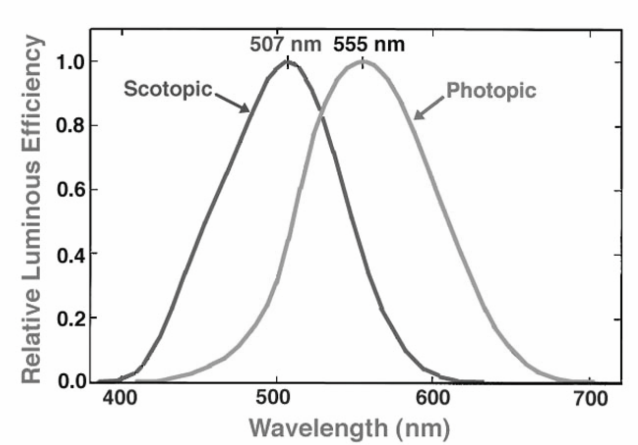


Figure 1.1 – Relative spectral response of the standard eye for photopic and scotopic vision

To calibrate the photodiode, you will use a calibrated light source which gives a known visual intensity for a given continuous electric current. The nominal values for the current, voltage and visual intensity, as well as their uncertainties, are written directly on the lamp.

P1 You will need to measure simultaneously the voltage and the current applied to the lamp. Give the circuit diagram which ensures the best precision for measuring the current.

1.1 Calibration method

Preparation

To calibrate a detector you have to measure its sensitivity as accurately as possible. The sensitivity (in μA/lm) is given by :

$$\sigma = \frac{i}{F_v} \tag{1.1}$$

where F_v is the visual flux received by the photodiode and *i* the resulting photocurrent.

P2 Recall the definitions and the units of the following quantities characterizing a source :

- intensity,

- luminance.

Each quantity is suited for a specific type of source : explain which kind and why. Recall the definitions and the units of the following quantities: visual flux, illuminance, geometrical etendue.

P3 Give the expression of the visual flux, F_v, received by a photodetector as a function of I_v, the intensity of a small source, d, the distance between the source and the detector, and S, the surface of the detector.

P4 How do you evaluate the uncertainty on the flux, knowing the intensity, the distance and their respective uncertainties?

Measurements

The calibrated light source is connected to a DC power supply which can be set between $0 - 250\,\mathrm{V}$. The voltage and current through the lamp should be precisely monitored using a voltmeter and an ampmeter. How do you connect the voltmeter and the ampmeter with respect to the lamp ? Why ? **Never exceed the nominal current and voltage of the lamp!** The photodiode will be placed on a moving mount and the calibrated light source at the end of the optical bench. Orient the photodiode and the calibrated light source to maximize the detected signal (the intensity of the light source corresponds to the maximum of the emission diagram).

$\leadsto$ **M1** Measure the sensitivity σ of the photodiode far from the light source (d > 1 m). Work in complete darkness. Try to minimize unwanted reflections and diffusions (stray light) with black stops.

Check your result with a teacher.

1.2 Analysis of the uncertainty budget

Q1 Express the relative uncertainty $\frac{\Delta\sigma}{\sigma}$ as a function of the following relative uncertainties:

- $\frac{\Delta F}{F}$, the relative uncertainty on the flux received by the photodiode,
- and $\frac{\Delta i}{i}$, the relative uncertainty on the photocurrent.

In the following questions, you will identify the different sources of uncertainty which contribute to these two uncertainty terms.

Relative uncertainty on the flux received by the photodiode

Q2 Express the relative uncertainty $\frac{\Delta F}{F}$ on the flux received by the photodiode as a function of the following relative uncertainties:

- $\frac{\Delta d}{d}$, the relative uncertainty on the distance between the source and the photodiode,
- and $\frac{\Delta I}{I}$, the relative uncertainty on the visual intensity of the lamp.

$\rightsquigarrow$ **M2** Perform the measurements required to evaluate these uncertainties.

Q3 For the visual intensity of the lamp, in addition to the uncertainty of ± 1 Cd due to its calibration at the nominal current, you have to account for the uncertainty on the measurement of the electrical current flowing through the lamp. Evaluate experimentally the influence of this uncertainty; to do so, measure how the photocurrent delivered by the photodetector varies when the electrical current through the lamp is varied around the nominal value.

Relative uncertainty on the photocurrent

Q4 Evaluate the relative uncertainty $\frac{\Delta i}{i}$ on the photocurrent due to the relative accuracy of the picoampmeter (given on the back side of the picoampmeter).

Relative uncertainty on σ. Propagation of uncertainties.

Q5 Deduce from the previous study an estimation of the relative uncertainty on your measured value of σ. Comment on the relative contribution of the various noise sources. We recommend to make a table showing these contributions in decreasing order, and their quadratic sum.

2 Measuring the luminance of an extended source with the calibrated photodiode

From the previous measurements, the detector is now calibrated and can measure a flux in visual units. In this section, you will measure the visual luminance (Cd/m^2) of a very bright white LED source. The fact that this source is almost uniform and lambertian will be assessed in the last part of this lab.

The luminance of a source describes its brightness. A source of high luminance is a very bright primary or secondary light source.

Typical examples of sources and their luminances :

	Luminance in Cd/m^2
Energy saving lamp (Hg)	5 000
Power Led	$2\ 10^7$
Blue sky (or full moon)	3 000
Sun	$1.6\ 10^9$
Snow (under the sun)	10^4

A light source may cause uncomfortable glare between 3 000 et 10 000Cd/m^2 Cd/m^2, glare becomes neutralizing. Even a moderate uncomfortable glare can impair vision.

2.1 Direct measurements with the single photodetector

⇝ **M3** To control the area of the LED source, place a diaphragm directly in front of it. Adjust the diaphragm to a diameter of 50 mm.

Q6 We wish to measure the luminance of the source with the single detector calibrated in the previous paragraph. Place the detector at a distance $D = 1$ m of the source. Calculate the geometrical etendue of the light flux in this configuration.

⇝ **M4** Perform 10 measurements of the luminance of the LED source by placing the photodetector on the bench at 1 m away from the source, and then as far as possible from the source. You will also modify the diameter of the diaphragm in front the LED source.

Q7 Comment on your measurements. Show in particular that they depend neither on the distance D nor on the diameter of the diaphragm, and evaluate the uncertainty on your measurements.

2.2 Measurements with an optical system and the same photodetector. Pupil of the system and geometrical etendue.

⇝ **M5** Place a lens (focal length $f = 120$ mm and f-number $N = 3$) between the white source and detector, in the $2f - 2f$ imaging configuration .

Q8 Describe the method you used to precisely reach this imaging configuration.

⇝ **M6** Measure the light flux received by the detector in this configuration.

Q9 Deduce from this measurement the luminance of the source and the illuminance received in the image plane. You will specify the geometrical etendue used in this configuration (using a simple schematic diagram).

⤳ **M7** Change the imaging configuration whist maintaining a detector size larger than the source image. Measure again the received flux, the luminance of the source and the illuminance in the image plane.

Q10 Comment on these measurements and explain the results.

⤳ **M8** Move the lens such that the transverse magnification is much smaller than 1. Explain your adjustment method.

⤳ **M9** Check that in this case, the detector collects all the flux received in the image plane.

⤳ **M10** Measure the light flux received by the detector in this configuration. Once again, deduce the luminance of the source from this measurement.

Q11 Comment on the latter measurements. Specify the geometrical etendue used in this configuration (using a simple schematic diagram). Explain why the latter measuring setup is not suited for measuring the illuminance in the image plane.

3 Measurements with a luminance-meter and a spectro-luminancemeter

In this section, your measurements will be compared to those given by two commercial instruments for measuring the visual luminance of extended sources (in Cd/m^2):

- a luminance-meter `LS-100 Minolta`
- a spectro-luminancemeter `SpectraScan PR 655 PhotoResearch`.

Q12 From the manual of the luminance-meter, describe the working principle of this instrument. Compare to the methods implemented above ?

$\leadsto$ **M11** Measure the luminance of the source with the luminance-meter `Minolta`. Describe your procedure. Compare with the values obtained in the previous section. How do you verify experimentally if the light source is Lambertian ? Perform several measurements with the luminance-meter.

Q13 Explain with a schematic diagram how the geometrical etendue is precisely defined (and constant!) in the luminance-meter. Compare to the methods proposed in the previous section.

In the manual of the spectro-luminancemeter, a simplified operating principle is described (see Fig. 1.2).

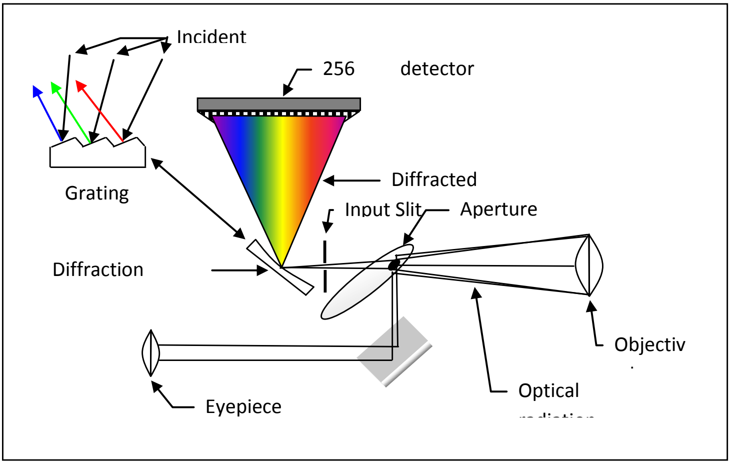


Figure 1.2 – Principle of a `PhotoResearch` spectro-luminancemeter .

Q14 Describe the measurement made by the spectro-luminancemeter. Compare it to the measurement performed with the luminance-meter.

$\leadsto$ **M12** Perform a luminance measurement of the source with the spectro-luminancemeter. Compare it to the values obtained in the previous section and using the luminance-meter.

$\leadsto$ **M13** Display the spectrum and its color coordinates. Comment on the measurements.

4 Measurement of the luminance of a secondary source

P5 Recall the definition of the albedo of a Lambertian scattering surface.

P6 Prove the relationship $L_d = \rho E_R/\pi$, where L_d is the luminance of the scattering surface (assumed to be Lambertian), E_R is the illuminance received by the surface, and ρ is the albedo of the scattering surface.

$\leadsto$ **M14** Place a white screen on the bench in front of the LED source, perpendicular to the main direction of emission. Using the luminance-meter `Minolta` test experimentally whether the screen is a Lambertian secondary source or not. Perform several measurements of the luminance in various directions of observation and comment on your measurements.

Q15 Deduce an estimation of the albedo of the screen. How accurate is your estimation ?

Lab work 2

Performance of lighting sources

Version: August 31, 2021

Questions P1 to P6 must be prepared in advance

The report must be sent within one week. Its length must be 8 pages maximum.

Contents

In this session, you will characterize the electrical, photometric and colorimetric properties of several lighting sources. Different measurements will be carried out for each source:

- **Electrical measurements**, using a Watt-meter, a Voltmeter, and an ampmeter.
- **Photometric measurements**, using a simple visual photodetector and an integrating sphere. You will measure the visual intensity and total flux.
- **Colorimetric measurements**, using a CRI illuminance-meter (*luxmètre-chromamètre*). You will measure the emission spectrum of the light source and its coordinates in the chromaticity diagram.

The integrating sphere needs to be calibrated (part 3) before

- analyzing the radiation of a tungsten wire (part 4),
- and comparing the performance of various lamps (part 5).

The lamps under study are commercial lamps (230 V) kept in their original packaging. You will report the relevant features provided by the manufacturer on the packaging of these lamps.

Important Note The interpretation of the measurements must be made on the spot, during the lab, and if possible controlled by the lab instructor. All the results will be given with an evaluation of the measurement uncertainty.

1 Preparing questions

P1 What properties of the black body radiation do the Stefan law and the Wien law describe ?

P2 Recall the emissivity of a grey body ?

P3 What is the definition of a Lumen?

P4 What is the maximum luminous efficacy (ratio of the luminous flux, in Lumens, to the electrical power supplied) that can be achieved with a monochromatic source? At which wavelength? Can we get a higher value with a wide spectrum source?

P5 What is the value of the luminous efficacy of solar radiation?

P6 What is the power factor of an electrical appliance or installation ? Why do electrical energy suppliers penalize manufacturers if their power factor is too low?

2 Flux and luminous efficacy measurements.

2.1 The integrating sphere

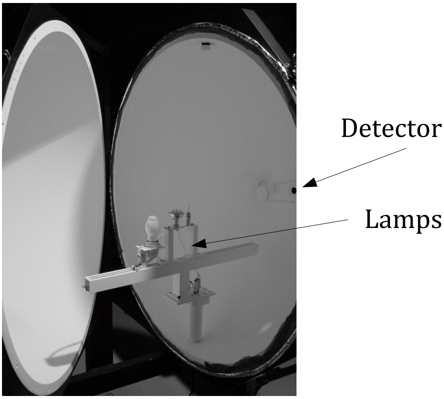


Figure 2.1 – The integrating sphere from LabSphere at LEnsE.

An integrating sphere (fig. 2.1) is a photometric instrument designed to measure the **total flux** emitted by either a directional (Laser) or a non-directional (LED, lamp,...) light source. It is a spherical cavity, the internal surface of which is a very good light diffuser (high albedo, ρ, and nearly Lambertian). The source under study is placed inside the integrating sphere. Light emitted by the source is submitted to multiple diffusions inside the sphere, leading to an homogenous irradiance that can be measured by a detector with known area, placed at the surface of the sphere.

⇝ **M15** Carefully open the sphere.

⇝ **M16** Please, **never touch the white paint, which is extremely fragile!**

⇝ **M17** Locate the reference lamp, the visual photodetector, and the classic lamp holder.

⇝ **M18** Note the presence of a small diffusing screen occulting any direct flux from the source to the detector.

2.2 Why is the integrating sphere the ideal instrument to measure a total flux ?

Assuming that the surface of the sphere is perfectly Lambertian, there is a simple relationship between the luminous flux emitted by the source and the illuminance inside the sphere :

$$E = \frac{\rho}{(1-\rho)} \cdot \frac{1}{4\pi R^2} \cdot F_{\text{lamp}},$$

where E (as *Éclairement* in french) is the illuminance (in luminous units, i.e. *lux*) and R the radius of the integrating sphere.

This formula is established under ideal conditions, where all the defects of the sphere (apertures in the inner wall, source, screen...) are neglected.

This formula can be demonstrated as follows : we first recall that the albedo of a surface is the ratio of the total flux reflected (or scattered) to the total flux received by the surface:

$$\rho = \frac{F_{\text{scattered}}}{F_{\text{received}}}$$

The illuminance of the detector is calculated as follows. By not taking into account the direct flow from the source to the sphere (which is the case for the detector, since it is masked by a cache and receives only indirect flux) and neglecting leaks (holes in the sphere), the flux received by the whole surface of the integrating sphere is the total flux emitted by the lamp diffused a large number of times on the sphere. This indirect flux is given by the expression:

$$F_{\text{Indirect}} = F_{\text{lamp}} \left(\rho + \rho^2 + \rho^3 + \cdots\right) = \frac{\rho}{(1-\rho)} F_{\text{lamp}}$$

If the surface of the sphere is perfectly Lambertian, after the first reflection (and for all following reflections), the flux received by the sphere is uniformly distributed.

The illuminance of the surface of the sphere due to the indirect luminous flux is simply:

$$E = \frac{F_{\text{Indirect}}}{S_{\text{Sphere}}} = \frac{1}{4\pi R^2} F_{\text{Indirect}}$$

where S_{Sphere} is the surface of the integrating sphere.

The **radius** of the integrating sphere is $50\,\text{cm}$. A calibrated source is positioned at the center of the sphere, together with the socket in which lamps under test will be plugged (fig. 2.2).

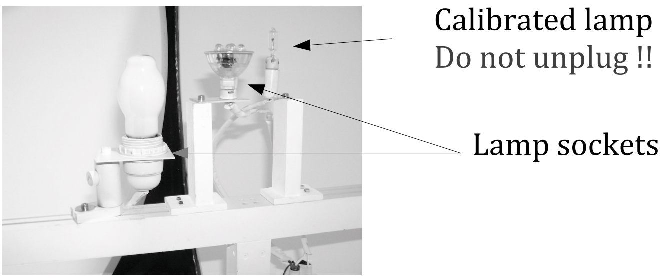


Figure 2.2 – Lamp sockets

2.3 Description of the visual photodetector

The visual photodetector is placed on the surface of the sphere and the output current is measured with a pico-ampmeter through a BNC cable. The photodetector is a silicon photodiode PIN-10AP with a ”$V(\lambda)$ filter”. Its sensitive surface is a disk of area $S = 1.000\ cm^2$. Incident light on the detector creates a current across the device, which can be directly measured by a pico-ampmeter (fig. 2.3). The pico-ampmeter accuracy is given by :

$$\boxed{\pm(0,5\% + 0.004 \times 10^{-3}\mathrm{A})}$$

The calibration of this kind of detector with a reference lamp has been studied in the labwork "Measuring luminance". The detector used during this session has been recently calibrated. Its sensitivity is :

$$\sigma = (366 \pm 13)\,\mu\mathrm{A/lm}$$

Knowing the area S of the detector one can derive the luminous flux and the illuminance. These measurements in visual photometric units are expressed in:

- Lumen (lm), for the flux,
- Lux (lx), for the illuminance.

Figure 2.3 – Control panel.

2.4 Characteristics of the reference lamp

To calibrate the integrating sphere, we use a reference lamp with a well-known total flux for a given current:

REFERENCE LAMP LUMINOUS FLUX

Current	Flux
(4.280 ± 0.015) A	(700 ± 70) lm

The reference lamp is a low voltage halogen lamp (12 V, 50 W). It is supplied by a regulated voltage. **Do not exceed** 12.3 **V !**

Q1 Following these characteristics, what is the luminous efficacy of the reference lamp ?

3 Calibration of the integrating sphere

$\rightsquigarrow$ **M19** Determine, with its uncertainty, the coefficient κ defined as the ratio of the current delivered by the visual photodetector to the total flux of the lamp inside the integrating sphere :

$$\kappa = \frac{i_{\text{Photodiode}}}{F_{\text{lamp}}}$$

4 Black body radiation. Study of the radiation of a tungsten wire.

In this section you will study the radiation emitted by a flat wire tungsten lamp, supplied by the dc power supply `ELS ALR3220`.

Caution Do not disconnect the lamp from its power supply !!

How to use the power supply The start-stop switch is on the rear planel. To adjust the value of the current, push on the `A` button, then `Select digit` and + or - to adjust the current.. Finally, push on the `On/Off` button to deliver current through the lamp. The supply displays the current, the voltage and the power delivered.

$\rightsquigarrow$ **M20** Increase progressively the current whilst observing the filament. Explain the change in colour of the filament when the delivered electrical power increases.

The Minolta illuminance-meter allows to measure the spectrum of a light source and to deduce the colorimetric coordinates. When the source is a black or grey body, the illuminance-meter also measures its absolute temperature in Kelvin. Here are the steps to follow to use it :

- perform the calibration of the dark signal of the instrument by rotating the ring and selecting `CAL`.
- Rotate the ring and select `ambiant light`.
- Select the menu `Spectrum` or `Triangle des couleurs CIE 1931` on the touch screen
- Orient the sensor (behind the white diffuser) toward the light source et click on `Measure` until the measurements are displayed.

$\rightsquigarrow$ **M21** Vary the dc current I flowing through the flat wire tungsten lamp by increments of 2 A between 8 and 16 A, and measure the values of

- the voltage,
- the electrical power supplied, P_{elec},
- the temperature of the lamp T (with the sphere open to place the illuminance-meter close to the flat wire),
- the total flux emitted F_{tot} (with the sphere closed, using the calibration of the sphere performed in section 3.

Q2 Assuming that all the electrical power supplied is transformed into flux radiated by the lamp, how should this power evolve with the temperature in Kelvin of the flat wire ? According to which law ?

Q3 Plot the curve of the evolution of the power P_{elec} versus T^4.

Q4 Deduce the value of the product

$$S_f \times \sigma_S \times \varepsilon$$

where S_f is the area of the flat wire (in m^2), ε is the tungsten emissivity (unitless) and σ_S is the Stefan constant (in $\text{W}/(\text{m}^2.\text{K}^4)$).

The filament has a length of $28 \pm 3\,\text{mm}$ and a width of $2.3 \pm 0.2\,\text{mm}$.

The emissivity of tungsten is 0.4 ± 0.1 for values of temperature between 2000 and $3000\,\text{K}$, and measured in the $400 - 800\,\text{nm}$ wavelength range.

Q5 Evaluate the area of the emitting wire, and deduce an experimental value for the Stefan constant. Compare to the theoretical value ($S_f = 5.67{\times}10^{-8}\,\text{W}/(\text{m}^2.\text{K}^4)$).

Q6 Plot the curve of the luminous efficacy of the flat wire tungsten lamp versus the supply current.

Q7 Comment the shape of this curve. What is the maximum value of the luminous efficacy for this lamp ? Why is this maximum obtained for the maximum temperature ?

5 Characterization of some light sources

We wish to study different types of commercial lighting lamps supplied directly by the mains with 220/240 V E27 base (27 mm diameter threaded cap). Below is an example of a technical sheet:

Specification

Model	Philips MASTER Spot LED PAR30 E27 9.5W
Lamp Type	LED PAR30
Wattage	9.5W (Equivalent to 75W)
LED Chip	Philips
Lumen	650 lm
CRI	80 Ra
Dimmable	Yes
Material	Cast Aluminium
Finishing Color	Grey
Dimension (D x H)	92mm x 94.1mm
Weight	0.5kg
Color Temperature	2700K Warm White
Beam Angle	25°
AC Input	220 - 240V
Power Factor	0.9
Average Lifetime	40,000 Hours
Warranty	12 Months

Figure 2.4 – Example of a technical data sheet for a lighting lamp

Q8 Explain and comment on the characteristics given in the data sheet.

⇝ **M22** Perform the following measurements for the lighting lamps chosen by the professor :

- Measure the total visual flux (in Lumen) and the electrical power consumed by the lamp (in Watts). Deduce the luminous efficacy of each source.
- Measure the power factor.
- Measure the spectrum, the correlated colour temperature (CCT), and the color rendering index (CRI).

The color rendering index of a source indicates how the source compares to a reference source (daylight or incandescent light) as far as visual rendering of colored samples is concerned. The CRI is defined by comparison to a reference source of the colorimetric results obtained from 15 calibrated samples. It can be directly calculated from the spectral luminance of the source.

⇝ **M23** Measure the CRI of the previous lamps and also of a mercury-vapor lamp using the illuminance-meter `KONICA-MINOLTA CL-79F`.

Q9 Which source has the best or the lowest luminous efficacy? Explain why.

Q10 Which source has the best color rendering index? Explain why.

Q11 Why is the power factor close to 1 for a halogen lamp ? How do you explain that it is lower than 1 for some LED lamps ?

Q12 Compare the color temperatures of the previous lamps. Explain their significance. For which lamp(s) does this measure have a physical meaning?

6 Results synthesis

Answers to the questions **E3** and **E4** should be given in the report.

E1 Synthesize and analyze your measurement results for each lamp.

E2 Compare the studied lamps from an economic and from a colorimetric point of view.

E3 Look for information to compare the environmental impact of their production, use and recycling.

E4 Search on the internet if there are more efficient and powerful lamps... still acceptable from a colorimetric point of view.

Lab work 3

Photometric characteristics of two objectives

Version : August 31, 2021

Question P1 to P5 must be prepared before the lab !

The report must be filed on the website within one week. Its length must be 8 pages maximum.

Contents

The goal of this lab session is to measure the photometric properties, in the visible part of the spectrum, of two photographic objectives of 50 mm focal length. One of them, with a metallic grey colour, is an old design ; the surfaces of its lenses are *not* anti-reflection coated. The design of the other one is more recent and its optical surfaces are anti-reflection coated. ***Indicate in your report the serial number of the objectives under test.*** You will perform the same measurements for the two objectives, in order to compare them; you will synthesize your results at the end of your report.

An ideal objective should give an image which exactly reproduces the scene observed, in term of luminance (we do not consider here the effect on the image of the limited spatial resolution of the objective). We recall that the illumination in the image plane of an optical imaging system, for an extended object, is given by:

$$E = \tau \pi L_{\text{objet}} \sin(\alpha_{\text{img}})^2 \quad (3.1)$$

where τ is the transmission factor and $\sin(\alpha_{\text{img}})$ is the image numerical aperture.

Figure 3.1 shows a perfectly black object (zero luminance) on a bright background (uniform luminance). In the image plane of the objective, with a given magnification, the same spatial variation of illuminance should be observed. The dashed line shows, with some exaggeration, what is obtained in reality: some stray light in the dark zone (1), a bright zone attenuated by the transmission of the objective (2) as well as its numerical aperture (3) and vignetting, which significantly reduces the flux on the edge of the field (4).

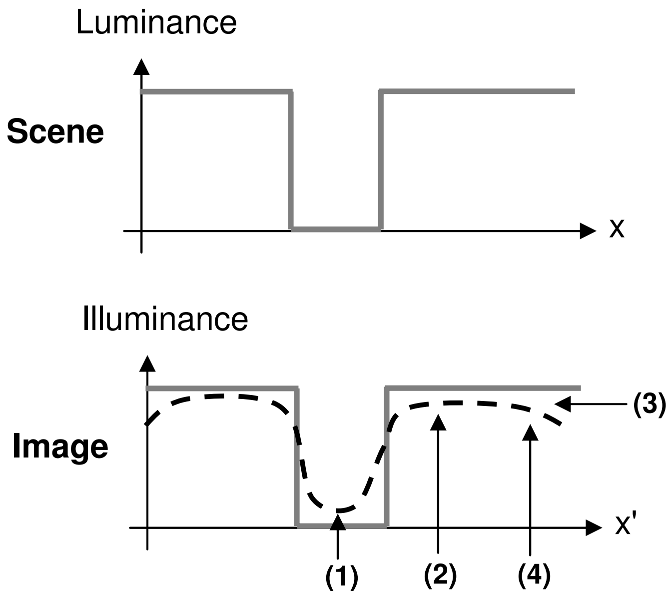


Figure 3.1 – Image given by a non perfect objective of a black object on a bright background.

P1 What is the definition and the unit of illumination ?

P2 What is the definition of the f-number of an objective ?

P3 For a plane object at infinity, what is the relationship between the f-number and the numerical aperture in image space ? How do you prove this relationship ? Under which condition on the aberrations of the lens is this relationship valid ?

P4 Recall the proof of formula 3.1 and show that for an infinite-focus conjugation the illumination in the image plane is given by $E = \tau\pi L_{\text{objet}}/4N^2$.

P5 Why do two successive f-numbers differ by a factor $\sqrt{2}$? The largest f-number (smallest aperture) of the black objective is 22. Write down all the other f-numbers available for this objective.

P6 Describe the causes that can limit the transmission factor τ of an optical system.

Equipment

In the last part of this lab, the black objective should be mounted on a USB camera Ueye, which relies on a CMOS sensor of the following dimensions : $6.9\,\text{mm} \times 5.5\,\text{nm}$. The size of the pixels is 5.3 microns × 5.3 microns (1280 × 1024 pixels).

Q1 Taking into account the focal length of the objective, calculate the corresponding object field of view.

The **detector** is a silicon photodiode with a green filter (giving a spectral response similar to the human eye, see Figure 1.1 page 2). The detector has an area of $S = 1.0\,\text{cm}^2$ and is placed inside a tube with a hole at the front. The axial position of the detector can be changed in order to adjust the numerical aperture of the system. The measurement itself is done with a pico-ammeter.

The **source** itself is an integrating sphere with a uniform luminance. A 250 Watt lamp is placed inside the sphere (**maximum voltage is 10 V**). A light trap, useful to measure the stray light, is located at the back of the sphere.

1 Evaluation of the amount of stray light on the optical axis

Stray light stands for all the undesired light incident on the detector. In the case of an objective, it could be light diffused by the metallic frame, an even number of reflections on the various lenses or stray light due to some dust particles on the optics.

Q2 What is the effect of stray light on the quality of the image given by the objective ?

In order to measure the level of stray light, we are going to use the light trap inside the integrating sphere. Its luminance is roughly 10,000 times smaller than the rest of the sphere and it can be considered as a perfectly black object. To have an independent measurement, we define $\mathbf{T}_P$ as the ratio of the illuminance in the image of the light trap given by the objective over the illuminance in the image of the integrating sphere.

Q3 Explain this definition.

⇝ **M24** With the help of a luminancemeter, measure the luminance of the integrating sphere. How uniform is the luminance of the sphere ? Perform a few measurements to evaluate this uniformity.

⇝ **M25** Using the luminancemeter, try to measure the luminance of the light-trap.

Q4 Evaluate the ratio between the luminance of the light-trap and the luminance of the sphere. Why is the measurement of the light-trap luminance very inaccurate ?

In order to measure the level of stray light induced by the objective, you will image the light-trap on a very small hole, i.e. with a diameter smaller than the diameter than the image of the light-trap through the objective. The photodiode capped with its green filter and placed right behind the small hole will measure the amount of stray light.

⇝ **M26** Check that the objective is clean (no dust). Clean it if necessary (Ask the teacher how to clean it !)

⇝ **M27** Adjust the detection hole very precisely in the image plane of the objective and on its optical axis. To do this:

- Find approximately the position of the image plane with a white paper screen and place the detection hole in that plane.
- Using the low magnification microscope viewer, superimpose the hole and the image of the light-trap and reduce as much as possible the parallax phenomenon.
- Then place the photodiode right behind the hole.
- Fine adjust the position in X, Y and Z of the hole, and minimize very carefully the incident power on the photodiode.

Special care must be taken for this delicate adjustment. Explain with a schematic the method used to find the absolute minimum value (as a function of X, Y and Z), i.e. the method used to optimize the minimum using the three degrees of freedom (longitudinally and in the plane XY).

⇝ **M28** Measure $\mathbf{T}_P$, the ratio of the minimum illuminance measured by the pico-ampmeter (on axis, inside the image of the light-trap) over the maximum illuminance (off-axis, away from the image of the light-trap), for both objectives (the black one and the grey one).

Q5 Why is this measurement very sensitive to the lateral and longitudinal position of the detection hole?

2 Transmission on the optical axis

Q6 What is the definition of the transmission factor τ of an objective?

To measure a transmission factor, it will be necessary to measure two flux: **before** and **after** the objective. The geometrical etendue of the two measurement configurations (with and without the objective) must be exactly the same. In practice, you will measure the flux detected without the objective, and then the flux detected in the image plane of the objective (or the inverse, i.e. the flux received with the objective and then without it).

Q7 A small hole placed in the image plane of the objective under test, followed by a photodiode far enough from the hole, defines a constant geometrical etendue (with or without the objective). Explain this assertion with a simple schematic, showing the objective under test, the output pupil, the detection hole and the photodiode with surface $1\,\mathrm{cm}^2$. Deduce from your schematic the minimal distance between the hole and the photodiode. In practice, you will use a brass tube and three brass rings that you can slide in between the detection hole and the photodiode.

Q8 Explain with a schematic the role of the three brass rings. In which order and orientation should you slide them in the brass tube ?

Q9 How do you check experimentally that the geometrical etendue is constant (with and without the objective) ? What happens when the numerical aperture is decreased too much (i.e. when the f-number is increased too much) ?

⇝ **M29** Measure τ, the transmission factor, using the brass rings and conclude. Repeat these measurements several times and evaluate the uncertainty of your result.

Q10 Conclude by giving the transmission factor of the objective, with its uncertainty. Repeat the measurement with the other objective.

3 Verification of the f-numbers

We now want to test experimentally the relationship between the illuminance in the image plane and the f-numbers reported on the objectives.

Q11 Explain with a schematic why the experimental configuration of the previous paragraph is not suitable. Propose a measurement configuration that allows you to measure the illuminance in the image plane, using the photodiode and the detection hole with diameter $1\,\mathrm{mm}^2$ placed precisely in that image plane.

⇝ **M30** Carry out the measurement of the current i_{ph} as a function of $\mathbf{N}$ - read on the objective aperture ring. Check that the detection hole is always set very precisely at the center of the image plane. Be careful not to aim the light-trap. Plot $i = f(\frac{1}{\mathbf{N}^2})$.

Q12 Compare to the expected theoretical prediction. How should you scale you axes to distribute your data points regularly ? Why ?

Q13 The deviation from the theoretical curve shows that some f-numbers do not match those on the ring of the lens diaphragm. What are these f-numbers? Try to explain why, for such f-numbers, the real values deviate from the expected ones.

We now want to plot the illuminance as a function of the f-numbers.

$\rightsquigarrow$ **M31** Measure the luminance of the integrating sphere in front of the objective, using the luminancemeter `Minolta`.

One gives the diameter of the sensor hole ($\Phi = 1\,\mathrm{mm}$) and the sensitivity of the visual detector (the photodiode capped by the green filter) :

$$\sigma = (359 \pm 8)\mu A/lm.$$

Q14 Plot the curve $E = f(\frac{1}{\mathbf{N}^2})$ and superimpose the expected theoretical curve on your graph (use the luminance of the sphere measured above). Comment.

4 Measurement of the Vignetting

For a number of applications, it is important to determine the vignetting of objectives, i.e. the decrease of illuminance at the edge of image field of view. The vignetting is often given in %, and represents the relative decrease of illumination, in the field, with respect to the illumination on axis.

$\rightsquigarrow$ **M32** To start, observe with your naked eye the exit pupil of the objective, and evaluate the full field angle by tilting the objective off axis. Then, evaluate the total field of view, for the three smallest f-numbers.

Q15 How do these angles vary with the f-number ? Using a schematic, explain why vignetting is important only at large numerical aperture, i.e. for small f-numbers.

Q16 Compare these values to the field angle associated to the dimensions of the CMOS sensor ($6.9\,\mathrm{mm}\times 5.5\,\mathrm{nm}$).

⤳ **M33** To characterize the vignetting at the edge of the image field (limited by the dimensions of the CMOS sensor), mount the objective on the USB camera. Then, place the camera just in the front of the opening of the integrating sphere and adjust the focus of the objective to image the interior of the sphere on the sensor.

⤳ **M34** Start the control software of the camera » `GUIVignettage` from Matlab. Parameters of the camera for this application are automatically loaded (Rolling Shutter, fixed gain, no Gamma correction - so the sensor response is linear). » `GUIVignettage` plots the illuminance profiles along a diagonal of the image and compares them when you change the size of the stop. An appendix to the manual of » `GUIVignettage` is available in the room.

⤳ **M35** Study ad measure the vignetting for the two or three largest numerical apertures, i.e. for the smallest f-numbers.

Q17 For each increase of the f-number, maintaining a constant grey level for the delivered signal requires that you adjust the exposure time of the camera. For instance, if the exposure time is $1\,\mathrm{ms}$ for $N = 2.8$, what exposure time should you choose for $N = 4$?

Q18 Comment on the results obtained for the evolution of the signal maxmum and of the vignetting with the f-number. Compare the two objectives in terms of vignetting.

Q19 Explain why the signal maximum varies when the f-number varies in spite of the adjustment of the exposure time of the camera.

⤳ **M36** Decrease the f-number to its minimal value whilst adjusting the exposure time to maintaining a constant grey level for the delivered signal.

Q20 What do you observe ? What is the shape of the spots that you observe in the image ? Where do they come from ? Is the measurement of vignetting relevant in this regime ?

5 Measurement of stray light directly on the image

⤳ **M37** Exit » `GUIVignettage` and launch the software
» `new_LumiereParasiteGUI`.

⇝ **M38** Image the light-trap on the camera and adjust the focus carefully.

⇝ **M39** Using the GUI, measure successively the dark signal of the camera (offset), the average value of the signal on a selected area of the light-trap, and finally the average value of the signal in the vicinity of the trap.

Q21 Compare the values of stray light obtained with the two methods proposed in this labwork. Propose an explanation for the observed differences. What has changedn fundamentally, between the two measurement configurations ? Can the phenomena observed above in Manip 4 explain the observed differences ?

Lab work 4

Science of color

La terre est bleue comme une orange

Paul Eluard. L'amour la poésie.
La couleur Fille de la lumière

Jean Jaurès.

The report must be deposited on the website within one week, and must not exceed 8 pages in length.

At the end of this labwork session you will be able to:

- Define and measure the colorimetric quantities of a light source,
- define the metamerisms (fundamental metamerism and illuminant metamerism),
- define and measure the colorimetric quantities of a colored surface,
- describe the phenomenon of chromatic adaptation of vision to a reference white.

Contents

1 Overview of the equipment at your disposal

Two industrial measuring instruments :

- a CRI Illuminance-meter (*luxmètre-chromamètre*) to measure light sources,
- a spectrophotometer (*spectro-colorimètre*) to measure the spectral reflectivities of various samples.

A lightbox and a computer screen Controlling their colorimetric parameters is the concern of part 4. A `Matlab` graph interfacing window allows to control the lightbox.

2 How to quantify the colored perception of a light source?

The color of a source or an object is not a physical quantity, it corresponds to a human perception.

However, scientists have tried for centuries to quantify this quantity, and our industrial societies need clean definitions to manufacture products and also to realize medical diagnostics using e.g. imaging techniques.

The colorimetric quantities, built during the last century, quantify nowadays the "color" of a light source. They are briefly reminded here. For more details you can refer to your colorimetry lectures notes[1].

The color perception is "trivariant"; this property is related to the presence of 3 types of cones in the retina of the human eye. It is not possible to quantify a visual perception with only one quantity.

The XYZ tristimuli are three quantities in $\mathrm{cd/m^2}$, i.e. visual luminances, defined from the spectral decomposition of the source under study in the visible spectrum[2]. Figure 4.1 recalls their definitions.

Note concerning the construction of these three quantities:

- The functions $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ are positive and null. They were defined in 1931, and constitute the CIE 1931 norm, they correspond to linear combinations of the spectral sensitivities of the sensors of the retina;

[1] *Colorimetry - Bases and applications*, 2nd year Lectures notes at IOGS-Palaiseau (2AP) by Hervé Sauer, and *Colorimetry*, 2nd year Lectures notes at IOGS-St Etienne (2AS) by Mathieu Hébert

[2] Note that the solid angle of the CRI Illuminance-meter being calibrated the measured tristimuli are actually illuminances, in lux.

$$X = K \times \int_{\text{visible}} \bar{x}(\lambda).L_\lambda(\lambda).d\lambda$$

$$Y = K \times \int_{\text{visible}} \bar{y}(\lambda).L_\lambda(\lambda).d\lambda$$

$$Z = K \times \int_{\text{visible}} \bar{z}(\lambda).L_\lambda(\lambda).d\lambda$$

Linear relationship $L_\lambda \mapsto \overrightarrow{XYZ}$

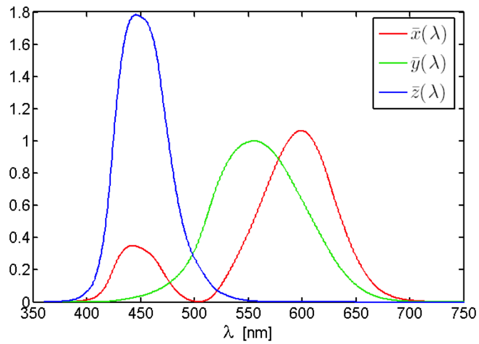


Figure 4.1 – Definition of the XYZ tristimuli starting from the spectric energetic luminance $L_\lambda(\lambda) = \frac{\partial L}{\partial \lambda}(\lambda)$ of a light source ($L_\lambda(\lambda) \geq 0$). Courtesy : Hervé Sauer, *Colorimetry - Bases and applications*, 2AP.

- The normalization coefficient is $K = 683\,\mathrm{lm/W}$, therefore X, Y, Z are in classical visual units.
- $\bar{y}(\lambda)$ has been chosen equal to the sensitivity function $V(\lambda)$ of the eye, Y is therefore the visual luminance of the light source (in $\mathrm{cd/m^2}$).

These quantities are sometimes normalized by the luminance of an ideal white (but not realizable in practice), i.e. a source the spectrum of which contains all wavelengths in equal amount, called "E white". The values of the tristimuli then become relative to each other, their relative weights characterizing the visual color perception of the source.

For memory Two sources with identical XYZ characteristics are observed with the same color by a human eye, and vice-versa. This *fundamental* property is at the basis of the CIE1931 XYZ system.

Representation of the chromatic "coordinates". The color cube. This definition using three quantities can be represented by the position in space of a point with coordinates (X,Y,Z). In the case of values normalized to the visual luminance of the E white, Y is restrained to $[0, 1]$ (but not necessarily X or Y); the color space is often represented as a cube of side 1 : the color cube. This is obviously an arbitrarily limited representation of color space.

Also, it should be noted that not all the points inside the cube correspond to actual visual perceptions, only a fraction of the cube corresponds to physically possible stimuli; this sub-ensemble (mathematically, a cone with vertex

(0,0,0)) is called the solid of actual colors and is (partially) shown (with a limited extent) on figure 4.2.

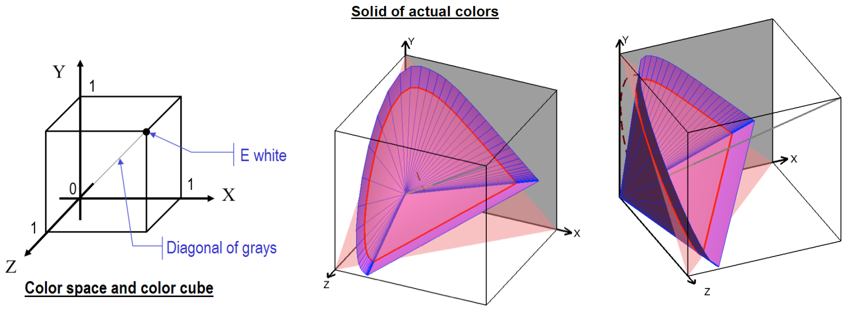


Figure 4.2 – Representation in the XYZ space of (a limited part of) the solid of actual colors. Courtesy : Hervé Sauer, *Colorimetry - Bases and applications*, 2AP.

The chromatic coordinates xy in the Maxwell triangle are also often used. They are defined by :

$$x = \frac{X}{X+Y+Z} \qquad \text{and} \qquad y = \frac{Y}{X+Y+Z}$$

They are built using the (conical) projection of the (XYZ) point onto the "diagonal" plane ($X + Y + Z = 1$) of the cube. They are shown in fig. 4.3.

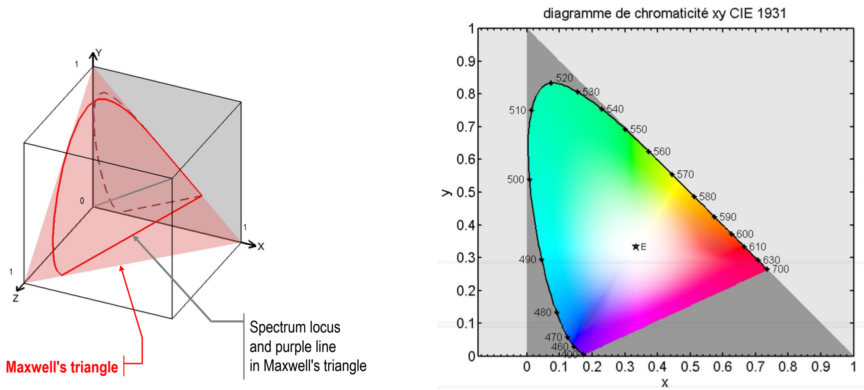


Figure 4.3 – Definition et representation of the chromatic coordinates xy in the Maxwell triangle (left). The projection in the $Z = 0$ plane yields the chromaticity diagram (right). Courtesy : Hervé Sauer, *Colorimetry - Bases and applications*, 2AP.

The cross-section of the solid of actual colors by the $X + Y + Z = 1$ plane contains the points of coordinates (xy) that are accessibles by real sources. It is delimited by :

- the *spectrum locus* (a convex line), the points of which correspond to a particular wavelength of the visible spectrum (monochromatic colors),
- the *purple line* (a straight segment), which connects the extreme points of the spectrum locus.

Many other colorimetric spaces have been defined, starting from the XYZ coordinates (L^*, a^*, b^* or $L^*, u^*, v^*, \ldots$). During this labwork session, only the XYZ tristimuli and the xy coordinates in the CIE1931 chromaticity diagram will be measured and analyzed.

3 Getting started with the CRI Illuminance-meter

The CRI Illuminance-meter at your disposal (see fig. 4.4) allows you to both quantify and analyze the spectral components of a source in order to deduce, after some numerical calculations, various quantities such as the colorimetric coordinates. This type of instrument works on the principle of a grating spectrometer, completed by some numerical processing.

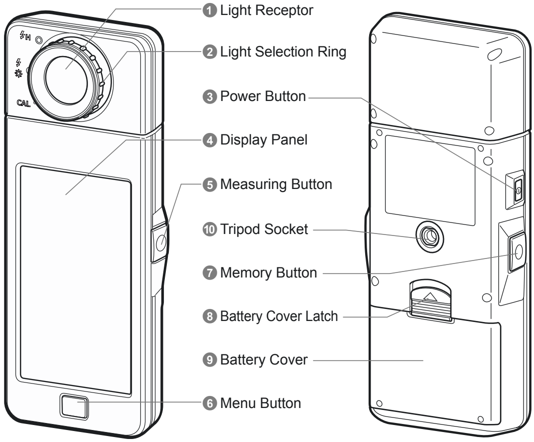


Figure 4.4 – CRI Illuminance-meter `KONICA-MINOLTA CL-70F`. Schematic from the datasheet given by the manufacturer.

⇝ **M1** Measure the spectrum of the room light. To do so :

- Switch on the instrument `CL-70F KONICA-MINOLTA` (*Power Button* ③).
- Realize the calibration of the instrument by selecting `CAL` with the rotating ring ② , fig. 4.4).
- Rotate the selection ring and select *ambiant light* (with the pictogram of a sun).
- Select the menu `Spectrum` on the touch screen.
- Orient the sensor (behind the white diffusive plate) towards the source and click on ⑤ : *Measure*.

⇝ **M2** Save the spectrum on the computer and display it. To do so :

- Connect the instrument to the computer using the USB cable,
- then launch the application `CL70F Utilitaire` by using the shortcut on the desktop.
- After the application has opened, select
  - the menu `Product Setting`,
  - then the tab `Tool Box`;

  - modify the line `Memory Title` using the following format `2017-MM-DD NamesOrGroupNumber`
  - then `ok` to close the window.

- In the instrument, go back to the menu `Spectrum` and click on *Memory*, ⑦.
- In the application `CL70F Utilitaire`, choose the menu `Memory Data` to display the spectra and the colorimetric data on the computer screen.
- To access the data (and save them as images) you can click on `Preview`. You can then copy the various graphs by "Copy to clipboard" and paste them into the Word file that you use for your report. Please save your files in the `MesuresColorimétrie` folder on the desktop, in a `RoomLight/` sub-folder for instance.

Q1 What the measuring range of the instrument in terms of wavelength?

Q2 Comment on the global shape of the spectrum. Which technology is the room light based on? What does the correlated color temperature of this source correspond to?

The (correlated) color temperature does not entirely characterize the color of a light source. It is defined as the temperature of the black body with closest chromatic coordinates (see fig. 4.5). It is used to qualify lighting sources with different "whites".

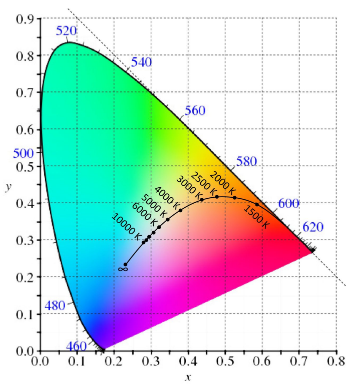
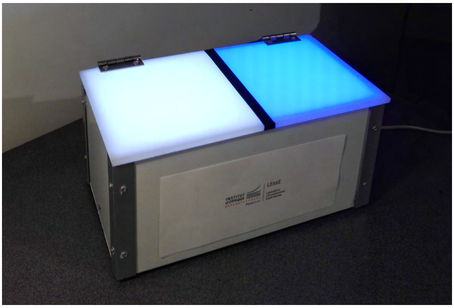


Figure 4.5 – Locus of CIE1931 chromatic coordinates of a black body versus its temperature (*Planckian locus*). Courtesy : Mathieu Hébert, "Colorimetry", 2AS.

4 Additive color mixing

4.1 Spectra and colors. Fundamental metamerism

Measure and perception. Comparison of two sources. In this part you will use the light box equipped with a diffusive opaline (fig. 4.6).



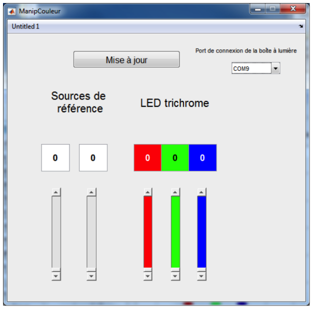


Figure 4.6 – Light box with two compartments used in this lab-work (left) and control window (right).

This box contains two compartments :

- in the left compartment there are two reference sources (`REF1` et `REF2`); a color filter can be placed in front of them;
- in the right compartment there is a ribbon of trichromic LEDs.

The sources are controlled (by pulse width modulation, PWM) by a microcontroller interfaced via a USB cable to the computer and the `Matlab` program.

⤳ **M3** Launch the interface program `ManipCouleur`. Test the ribbon of LEDs and its connection to the computer by successively driving the various sources. The control values must be integers between 0 and 255.

⤳ **M4** Measure and analyze the chromatic characteristics of the two reference sources using the CRI Illuminance-meter, for a control value of 255.

⤳ **M5** Measure the correlated colour temperature (CCT) of the two reference sources. Compare to the CCT of the room light and to the CCT of the sun.

Q3 Which reference source is "cooler" ? Comment by looking at the spectra of the two reference sources.

Q4 Where does the blue peak come from ?

⇝ **M6** Adjust the control of the ribbon of trichromic LEDs to obtain the same color (visually) as for `REF1`. Don't waste too much time on this equalization. Explain how you proceed to equalize the colors of the two compartments, and note the control values that you obtain.

Q5 Measure the x and y coordinates, and the X, Y and Z coordinates of the two reference sources. Are they close ? Compare the associated spectra.

Fundamental metamerism is the phenomenon demonstrated above. Additive color mixing uses this phenomenon. Indeed, one does not need to perfectly match two spectra to obtain identical colors. Matching the three colorimetric coordinates XYZ is sufficient.

4.2 Synthesis of colors using the trichromic LED

Characteristics of each of the three components

⇝ **M7** Measure the spectrum and the chromatic characteristics of

- the red component of the trichromic LED at its maximum value (255 0 0),
- the green component at its maximum value (0 255 0),
- the blue component at its maximum value (0 0 255),
- the blue component at half maximum (0 0 128),
- of the blue and green components simultaneously at their maximum values (0 255 255).

Save these measurements on the computer. Check the names of the various files.

Q6 Analyze and compare the two measurements performed on the blue component (at its maximum value and at half maximum). Compare in particular the values of

- the total visual luminance,
- the chromatic coordinates x and y.

and also the overall shape of the spectrum.

⤳ **M8** Place the three points corresponding to the three components at their maximum value on the chromaticity diagram using the program `DiagChroma` and save your graphic.

⤳ **M9** Place the point corresponding to the mixture of blue and green on the chromaticity diagram.

Q7 Analyze your results. Is the corresponding point aligned with the two points of each constitutive component ? Is it in the middle of the associated segment ?

Color gamut and triangle or reachable colors

To correctly perform an additive mixture one must work with the 3 chromatic coordinates. However, not all points (XYZ) inside the solid of actual colors can be reached. The reachable points define a solid, the so-called *color gamut*, shown on fig. 4.7. The intercept of the gamut by Maxwell's triangle is a triangle, which projects onto the (x, y) plane and yields the so-called "triangle of reachable colors". In addition, the discreteness of the control values of the sources lead in practice to a finite number of reachable colors.

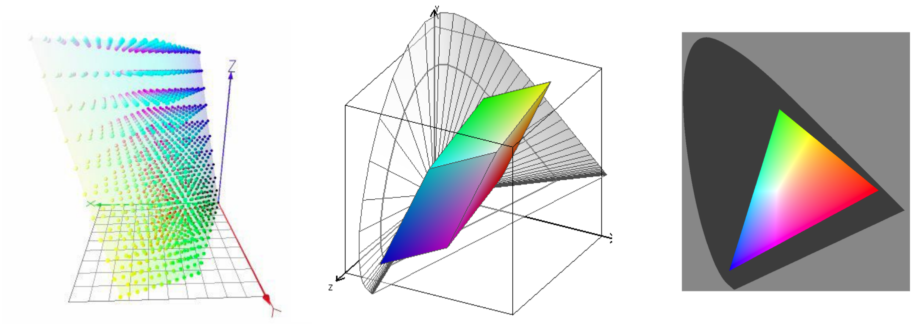


Figure 4.7 – Representations of the solid of reachable colors (*color gamut*) inside the color cube (left and center). The solid of reachable colors is actually discretized (left) due to the finite number of control values of the sources. Triangle of reachable colors in the (x, y) plane (right). An interactive 3D figure is also available (by typing »`SolideXYZ_synth_sRGB`) to help you visualize the gamut. Courtesy : Hervé Sauer, *Colorimetry - Bases and applications*, 2AP; and Mathieu Hébert, *Colorimetry*, 2AS.

Method of additive color mixing

One first needs to build the matrix of color mixing, starting from the three XYZ vectors of the red, green and blue components of the trichromic LEDs at their maximal power :

$$M_{\text{LEDtri}} = \begin{pmatrix} X_R & X_G & X_B \\ Y_R & Y_G & Y_B \\ Z_R & Z_G & Z_B \end{pmatrix}$$

The chromatic coordinates of the (white) light produced by mixing the three components at their maximal power will thus be :

$$\begin{pmatrix} X_{\text{white}} \\ Y_{\text{white}} \\ Z_{\text{white}} \end{pmatrix} = M_{\text{LEDtri}} \times \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

And if you wish to obtain a light with chromatic characteristic $\begin{pmatrix} X_{\text{target}} \\ Y_{\text{target}} \\ Z_{\text{target}} \end{pmatrix}$, the control values that you need to send to the LEDs should be proportional to :

$$M_{\text{LEDtri}}^{-1} \times \begin{pmatrix} X_{\text{target}} \\ Y_{\text{target}} \\ Z_{\text{target}} \end{pmatrix}$$

⇝ **M10** Following this method, use `Matlab` and the previous measurements to calculate the control values that you need to send to the LEDs to obtain exactly the same color as the reference source that you chose in question **M6**.

`Matlab` syntax, reminder :

- Create a 3×3 matrix : `M = [ a b c ; d e f; g h i];`
- Invert a matrix and multiply it by a vector : `inv(M)*V`

Q8 Check that the control values are consistent with the ones that you obtained by iterative adjustments in question **M6**.

⇝ **M11** Place an orange filter (and/or a filter with another colour) in front of reference source `REF1` or `REF2` set at an arbitrary power. Calculate the control values of the trichromic LED that lead to the same color. Verify your result experimentally.

⇝ **M12** Place the (xy) coordinates of each studied colored sources on the chromaticity diagram using the `DiagChroma` routine.

5 Chromatic adaptation - Balance of whites

$\rightsquigarrow$ **M13** Adjust the right side of the light box to obtain a source with chromatic coordinates $x = 0,4$ et $y = 0,4$. To do so, first determine X, Y and Z coordinates that fulfill this requirement, and then use the same method as above.

Q9 Switch on the source `REF1` on the left side. Which color would you say the right side of the light box is ? Yellowish, greenish ... ?

$\rightsquigarrow$ **M14** Perform the same experiment using your cell phone. Compare and comment the obtained images.

$\rightsquigarrow$ **M15** Switch off the box and switch on the desk light, so as to illuminate the left side of the light box. Put a screen between the two compartments of the light box so that the desk light does not illuminate directly the right side but you can still see the two sides simultaneously.

Q10 Has the apparent color of the right side been modified ?

The chromatic adaptation is the phenomenon demonstrated in this experiment. Our brain interprets colors differently depending on the average white of the surrounding scene. Cameras do the same during a shot; this phenomenon is called "balance of whites".

Q11 Verify that your observations are consistent with the two graphs in fig. 4.8, which gives indications on how a scene is perceived depending on the white reference that illuminates it (Munsell zones).

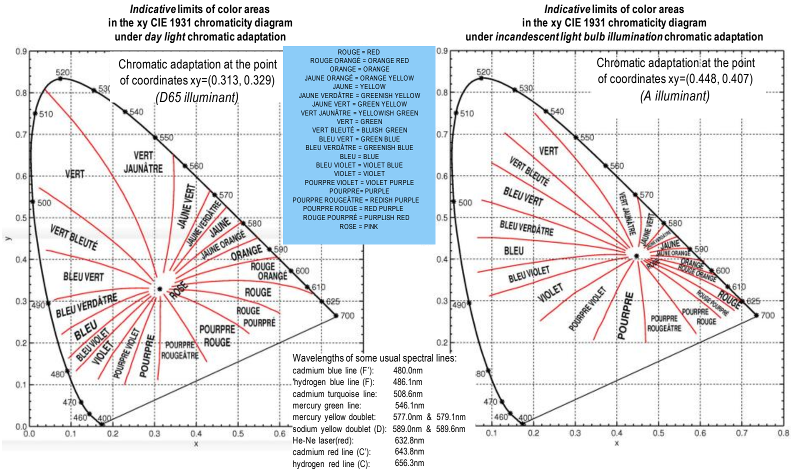


Figure 4.8 – Courtesy : Hervé Sauer, from the data of the Munsell atlas.

6 How to define and measure the color of a surface ?

« La couleur est Fille de la lumière» . The colour of a surface depends on the lighting source that illuminates the surface (the illuminant). The colorimetric characteristics of a surface can be defined or measured only for a given illuminant [3].

6.1 Definitions

The colorimetric characteristics are most commonly defined for :

- an illuminant `D65` i.e. daylight,
- and/or an illuminant `A` i.e. an incandescent light.

The CIE colorimetric quantities can be calculated from the spectral reflectivity $\rho(\lambda)$ of the surface under test.

[3] An "illuminant" is a "normalized" source est (i.e. defined by a norm) that allows a colorimetric characterization of surfaces under precise lighting conditions. The CIE has defined tens of illuminants, typical of e.g., daylight at certain hours [e.g. D65], incandescence lamps [A], various fluorescent bulbs [e.g. F11], etc...

Let $E(\lambda)$ denote the spectric illuminance (in $(\mathrm{W/m^2})/\mathrm{nm}$) received by the surface. In the case of a lambertian surface, the spectric luminance of the surface under test considered as a secondary source, is given by :

$$L(\lambda) = \rho(\lambda)\frac{E(\lambda)}{\pi} \tag{4.1}$$

The following definitions are easily obtained :

$$\begin{aligned} X &= G\int_{\text{visible}} \rho(\lambda)E(\lambda)\bar{x}(\lambda)d\lambda, \\ Y &= G\int_{\text{visible}} \rho(\lambda)E(\lambda)\bar{y}(\lambda)d\lambda, \\ Z &= G\int_{\text{visible}} \rho(\lambda)E(\lambda)\bar{y}(\lambda)d\lambda, \end{aligned}$$

where G is a normalization coefficient to get free of the source power :

$$G = \frac{1}{\int_{\text{visible}} E(\lambda)\bar{y}(\lambda)d\lambda}$$

Q12 How does one derive equation (4.1) ?

6.2 Measurement technique

The measurement of the spectric reflectivity is performed in a normalized configuration, by using for instance a diffuse illumination of the surface (realized in practice with an integrating sphere) and by measuring at an angle of 8°from the normal to the surface, with or without the specular reflection. The measuring device contains :

- a white source, associated to an integrating sphere in the case of diffuse lighting,
- a collection system of the flux scattered by the surface under test,
- a two-way spectrometer : one for the measurement, and one for the illumination of the surface.

The schematic of the spectrophotometer `KONICA MINOLTA CM2600d` is shown in fig. 4.9.

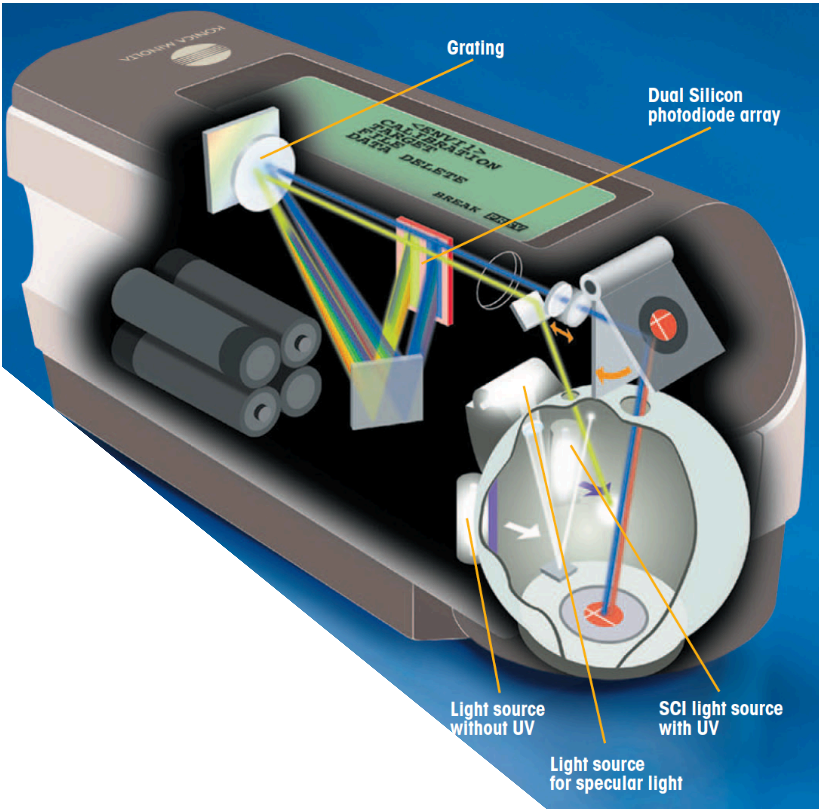


Figure 4.9 – Schematic illustrating the working principle of the spectrophotometer. Courtesy : KONICA-MINOLTA datasheet.

The `CM2600d` illuminates the sample under test with diffuse light using an integrating sphere, and measures the backscattered light at an angle of 8°from the normal to the surface of the sample ; the specular reflection on the (not necessarily Lambertian) sample can be included (or not), corresponding to the CIE normalized measure configurations:

- `di:8°` (`SPI`: specular reflection included)
- `de:8°` (`SPE`: specular reflection excluded).

6.3 Getting started with the spectrophotometer

⤳ **M16** Switch on the spectrophotometer and launch the `SpectraMagic` software. Then :

- connect the computer to the device using the `Instrument/connexion` menu;
- calibrate the device by following the software instructions. There are two steps : to calibrate the dark signal, a *light-trap* is available inside the leather pouch. For the calibration of the white, use the *calibrated "reference white"* on the support of the spectrophotometer; DO NOT put your fingers on the "reference white" after removing the protection cap; PROTECT AGAIN the "reference white" with the cap after calibration.
- place the instrument on the surface under test,
- perform the measurement (`Echantillon` menu)

The various menus are shown in fig. 4.10.

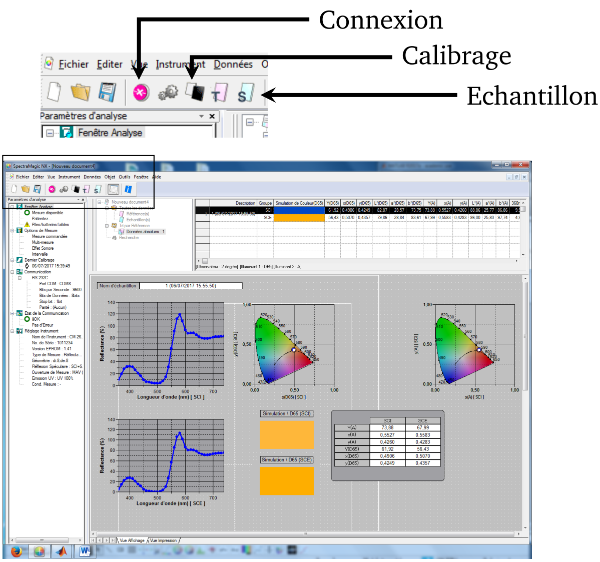


Figure 4.10 – Window of the spectrophotometer driver `SpectraMagic`.

6.4 Measurement of colored samples

⤳ **M17** Measure the spectral reflectivity of some colored paper samples on the table. Verify that your measurements are consistent with the aspect of the samples.

Q13 Are the colorimetric coordinates different under illumination by illuminant `D65` or illuminant `A` ? Does it make a difference visually ?

⇝ **M18** Perform the measurements for shining surfaces.

Q14 Analyze your results, in particular the differences (if any) between the measurements including the specular reflection (SCI) and those that exclude it (SCE).

Q15 Choose a coloured paper or any other obfect, and measure the x, y coordinates of the coloured paper using the luminancemeter Minolta. Synthesize the corresponding colour using the light box and the ribbon with red, green and blue LEDs. Comment on the agreement between the obtained colours.